Meta-Heuristic Approach for the Hazmat Shipment Scheduling Problem*

Pasquale Carotenuto† Stefano Giordani‡ Silvia Rismondo† ‡

†Istituto di Tecnologie Industriali e Automazione - Sezione di Roma -
Consiglio Nazionale delle Ricerche
Via del Fosso del Cavaliere 100, I-00133 Rome, Italy
{p.carotenuto,s.rismondo}@itia.cnr.it

‡Dipartimento di Ingegneria dell'Impresa
Università di Roma "Tor Vergata"
Via del Politecnico 1, I-00133 Rome, Italy
giordani@disp.uniroma2.it

1 Introduction

In recent years, there has been an increasing interest in the hazardous material (hazmat) transportation problem, and much work has been done to classify hazmats into class of risk in order to define a general purpose label system. This system can handle the emergency process whenever an accidental release of these materials happens, allowing to easily recognize the dangerous substance, and arrange the adequate emergency operations. At world wide level, hazmat transport activities involve about 4 billion of tons of transported hazmat (e.g., see Zografos and Androutsopolous (2004)), and for this reason these activities cover a remarkable role in the economy of industrial country being crucial for the industrial development policies, and certainly encouraging the research in this field. On the other hand, hazmat transportation activities could represent a serious risk for the population, and the environment as well, since hazardous materials are often employed not where they are produced, and then the risk related to an accidental release of them during the transport, has to be taken into account. In this work, considering as given the societal risk associated to the hazmat transported, we address the problem of how manage a set of hazmat transportation requests from origin-destination pairs, respect to the spatial, and temporal dimensions. In the literature, it may be underlined two main threads of research concerning the hazmat transportation field.

The first thread of research is related to risk assessment associated with shipping hazmats along a specified link of a transportation network. A wide literature has focused on risk assessment,

*This work has been partially supported by the GNDRCIE of the Italian National Research Council (C.N.R.) and Dip. Protezione Civile - Pres. Consiglio dei Ministri

and several works concern the modeling of the risk probability distribution over given areas, taking into account the risk related to the carried substance and the transportion mode (e.g., see Abkovitz, Eiger and Srinivasan (1984)), the environmental conditions (e.g., see Patel and Horowitz (1994)), and the selected route. A survey on the risk modeling can be found in Erkut and Verter (1998). The second research thread concerns the equity distribution of the risk, and low risk routes definition. These two aspects have to be considered to spread equitably the risk connected to the hazardous material shipment in the whole crossed area.

In the literature, several models have been proposed for determining routes of minimum risk under the tie of equity; see, for example, the model proposed by Gopalan, Batta and Karwan (1990), and Current and Ratick (1995). Gopalan *et al.* (1990), deal with the equitable distribution of the risk by considering a strip around every path (i.e., the area of impact), and by considering the population included in this area as equally subject to the consequences of the accident. Taking into account an equitable distribution of the risk, different methods have been proposed to find, given an origin-destination pairs, a set of alternative routes for the hazmat shipments (e.g., see Akgün, Erkut and Batta (2000), Lombard and Church (1993), Kuby, Zhongyi, and Xiaodong (1997), Carotenuto, Giordani and Ricciardelli (2003)). Indeed, these methods allow only to spatially spread equitably the risk over a region, but they do not consider the spreading of the risk over time. To the best of our knowledge, during the last decades, the temporal aspects of this spatial (routing) problem, that is the problem of scheduling hazmat shipments, has received very little attention. For instance, Cox and Turnquist (1986) propose a model for determining the best departure time of hazmat shipments on a given route containing cities with curfew. The model assumes that the link travel times are either deterministic, or stochastic variables.

It is important to notice that routes representing good solutions respect to the spatial dimension, could be bad if temporal aspects have to be take into account. Classical modeling approach for the hazmat transportation problem, often refers to extended versions of the vehicle routing problem, that is they consider in the model also risk values (e.g., see Zografos and Androutsopoulos (2004)), either in the objective function (mono o multi-criteria approaches), and in terms of constraints (i.e., risk threshold to be satisfied), while temporal aspects are introduced in the model in terms of time windows.

In this work, we focus the attention only on the scheduling hazmat shipments as explained next. We believe that the hazmat transportation problem can be defined as a scheduling problem under the following requirements:

1. each vehicle starts its route at the origin location, and terminates at the destination one, that is, each vehicle is dedicated only to a single hazmat transportation request;
2. the route does not contain intermediate stops;
3. the decision maker needs also to optimize time-basis performance.

The first requirement depends on the intrinsic nature of hazmat transportation problem. In fact, for some hazardous materials the hypothesis of pick-up and delivery could not be realistic. The second requirement is due to the fact that we just consider deliveries that respect the existing law for driver regulation, that is all the deliveries follow the working hours according to the national legislation. Finally, the objective function corresponds to the minimization of a temporal performance measurement as in the classical scheduling theory.

Based on the previous hypotheses, we propose a two stages approach that allow us to focus on the scheduling problem modeling, and resolution. In the first stage, a set of minimum and equitable risk alternative routes are generated for each couple of origin-destination points. In the second stage, addressed in this work, a hazmat shipment scheduling problem has to be solved, where a route among the generated ones in the first stage, and a departure time not less than a given preferred one, have to be assigned to each hazmat transportation request, so as to minimize the total hazmat shipment delay, while assuring to spread the risk of travel also respect a time basis requirement. For this hazmat shipment scheduling problem, we propose a job-shop scheduling model where the objective is minimizing the total job completion time. Indeed, the proposed model is an extension of the job-shop scheduling problem, where each job has alternative routes; that is, each job has different alternative chains of operations, and the problem consists in selecting for each job one of the alternative routes, i.e., a chain (sequence) of operations, and scheduling each job with the assigned route. In the scheduling model no-wait constraints arise as well, since when a hazmat shipment starts, it cannot stop its traveling, supposing that no safe area is available.

During the last years, different extension of the job-shop scheduling problem (JSP) have been proposed in the literature, and two main threads of research may be underlined in which interesting theoretical results have been obtained concerning the makespan minimization. The first research thread concerns the possibility of considering machine alternatives for individual operations. In this field, we recall the job-shop scheduling problem with multi-purpose machines (MPM-JSP) (e.g., see Brucker and Schlie (1990)), where each operation has an associated set of machines and has to be executed on exactly one out of these machines, the flexible job-shop scheduling (FLEX-JSP) (e.g., see Brandimarte (1993)), where operations may have different durations depending on the different machines, and the multi-mode job-shop scheduling (MMJSP) (e.g., see Brucker and Neyer (1998)), where each operation may be executed in one out of different execution modes, each one consisting in requiring a set of machines for a certain time period. A second thread of research studies the extension of the classical job-shop model with respect to the job routings, from the basic case in which they are chains of operations to the more general case in which job routings are general direct acyclic graphs, see Kis (2003). In this paper, the author studies the job-shop scheduling with processing alternatives (AJSP), where job routings are directed acyclic graphs recursively formed by sequence of graphs, and-subgraphs, and or-subgraphs.

Most of the previously models are heuristically solved by means of some kind of metha-heuristic approach (e.g., see Brandimarte (1993), Kis (2003), Dell'Amico and Trubian (1993), Mastrolilli and Gambardella (2000). The model we study in this paper is a special case of the AJSP in which each job routing is an or-subgraph where each branch is a chain of operations. Nevertheless, our model contains a set of constraints that are not included in Kis (2003), that is the no-wait constraints, requiring that the operations of a job must be executed without waiting time between two consecutive operations (e.g., see the survey in Hall and Sriskandarajah (1996)). The no-wait constraints are typical in many real-life industrial application where intermediate buffers between machines are not available. The no-wait JSP is known to be NP-hard in the strong sense also in the restricted case of two machines. For this reason many papers propose for this problem approximate procedures for specific production environments (e.g., see Macchiaroli, Mole and Riemma (1999), and Mascis and Pacciarelli (2002)).

We propose a meta-heuristic algorithm to solve a scheduling model that addresses the hazmat transportation problem, in terms of route selection and starting time definition for a set of Hazmat transportation requests. The algorithm is evaluated on a set of realistic test problems also with respect to route length, and risk indexes. In the following sections we formally define the hazmat scheduling problem, and give the proposed job-shop scheduling model.

2 Definition of the problem

We consider a road network $G = (N, L)$, where N is the set of nodes representing geographical locations, and L represents the set of direct links between pairs of nodes. A set $J = \{1, ..., n\}$ of n hazmat transportation requests (HTRs) are given, each one identified by a origin-destination pair of locations, with O_j, $D_j \in N$ being the origin and the destination, respectively, and by an associated preferred departure time r_j for leaving the origin O_j. For each HTR j, a set $R_j = \{\rho_{1j}, ..., \rho_{K_j j}\}$ of alternative routes on the network G is also provided, each one going from origin O_j to destination D_j.

The problem consists in shipping HTR j on a selected route of R_j, with a departure time s_j not less than the preferred departure time r_j. We suppose that the hazmat vehicles once departed have to travel on the assigned route without stopping at intermediate locations. The aim is to minimize the total delay with respect to minimum arrival times at destinations. While the given routes are assumed to be chosen so as to assure risk minimization and a certain equity of distribution of the risk over the population of the region crossed by the hazmat shipments, in order to spread the risk also over time, it is required that at any time the (Euclidean) distance between any two hazmat vehicles must be not less than a certain value λ. In order to represent this concept of risk spreading over time, we consider each route ρ_{hj} formed by a sequence of n_{hj} points $(x^1_{hj} = O_j, ..., x^i_{hj}, ..., x^{n_{hj}}_{hj} = D_j)$, with distance 2λ between two consecutive points, and define a λ-circle, i.e. a circular zone of radius λ, centered in each point, that may be traversed by at most one hazmat vehicle at a time. Figure 1 depicts the λ-circles of the route ρ_{hj} of the hazmat requests j.

3 The proposed scheduling model

For the hazmat shipment scheduling problem, we propose a job-shop scheduling model with alternative job routes. Viewing each HTR j as a job, the hazmat shipment (i.e., the execution of a job) on a route ρ_{hj} corresponds to executing a sequence $(o^1_{hj}, ..., o^{n_{hj}}_{hj})$ of operations without preemption, each one representing the traveling on the section of the selected route inside the λ-circle centered in point x^i_{hj} of the route. The operations of a job must be executed with no waiting time between their executions, since hazmat vehicle are assumed to travel without intermediate stops. Clearly, two operations defined on two intersecting λ-circles cannot be done simultaneously and hence are incompatible. Hence, each λ-circle Λ^i_{hj} behaves as a set M^i_{hj} of machines simultaneously required by the operation o^i_{hj}, which therefore can be seen as a multi-processor task. Formally, the job-shop scheduling problem we consider is defined as follows: A set J of jobs is given, with r_j being the release time of job j. For each job $j \in J$, a

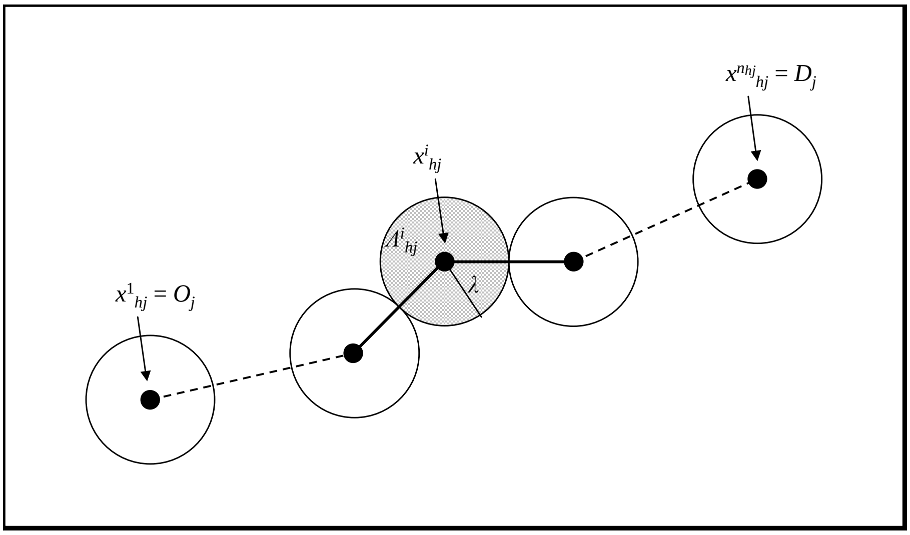

Figure 1: Route ρ_{hj} of j

set $R_j = \{\rho_{1j}, ..., \rho_{K_j j}\}$ of $K_j \geq 1$ routes are available, where each route $\rho_{hj} \in R_j$ identifies a sequence $(o^1_{hj}, ..., o^{n_{hj}}_{hj})$ of n_{hj} operations, each one, let us say o^i_{hj}, to be executed by a dedicated set M^i_{hj} of machines of the job-shop for a certain processing time p^i_{hj}. The rest of assumptions are: no machine can process more than one operation at a time; the processing of an operation cannot be interrupted; no two operations of the same job can be done simultaneously.

The problem is to select a route $\rho_{hj} \in R_j$ for each job j, that is, a sequence of operations to be executed with no waiting time between two consecutive operations, and a starting time, not less than the release time, for each job such that the total job completion time is minimized.

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